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ORIGINAL PAPER

Temporal dynamics and spatial variations of forest vegetation carbon stock in Liaoning Province, China

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Abstract: There are many uncertainties in the estimation of forest carbon sequestration in China, especially in Liaoning Province where various forest inventory data have not been fully utilized. By using forest inventory data, we estimated forest vegetation carbon stock of Liaoning Province between 1993 and 2005. Results showed that forest biomass carbon stock increased from 68.91 Tg C in 1993 to 97.51 Tg C in 2005, whereas mean carbon density increased from 18.48 $Mg \cdot ha^{-1}$ C to 22.33 $Mg \cdot ha^{-1}$ C. The carbon storage of young- and middle-aged forests increased by 22.1 Tg C and 5.95 Tg C, but that of mature forests has decreased by 0.25 Tg C. The carbon stock and density of forests in Liaoning Province varied greatly in space: larger carbon storage and higher carbon density were primarily found in the east area. The spatial distribution of carbon density was determined by many factors, of which human activities played an important role. The forests in Liaoning Province played a positive role as a sink of atmospheric carbon dioxide. The carbon fixation ability of forests in this area was primarily derived from forest plantation and the total forest carbon sequestration can be enhanced by expanding young- and middle-aged forests.

Keywords: carbon storage; carbon density; age structure; carbon-oriented forest management strategies

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Introduction

Currently, researches on global climate change are attracting widespread scientific and public attentions because of rising concentrations of carbon dioxide (CO_2) in the atmosphere. Interacting with atmospheric processes through photosynthesis and respiration, forest ecosystems play dominant roles in regulating global carbon cycle (Fang et al. 1996) because they are responsible for about more than 86% of overall vegetation carbon sink and about 73% for overall soil carbon sink on Earth (Lv et al. 2008). Compared with other methods of mitigating CO_2 emission under the background of global climate change, forests have their own specific advantages, such as lower cost and higher efficiency (Huang 2008). Hence, the Kyoto Protocol addressed that carbon sequestered by afforestation and reforestation could partly offset CO_2 emissions from fossil fuel consumption.

There are a variety of methods for estimating forest carbon stock, which can be divided into three categories: sample plot inventory method, ecosystem modeling method, and remote sensing method (Yang et al. 2005). Estimating forest resources by remote sensing has been studied for a long period. Landsat TM Images are mainly used to estimate forest volume, but can not directly measure factors related to volume and models have to be developed by using a variety of indirect factors (Feng 2008). Ecosystem models are necessary and have advantages in calculating changes in soil carbon and biomass by vegetation and soil types through scaling up processes with spatially-explicit climate data. However, the uncertainties of the ecosystem models still remain when calculating the effects of forest vegetation change on carbon stock (Wang and Sun 2008) because of differences in parameterizations of ecosystem processes and the complexity of input parameters (Yan and Zhao 2007). In comparison with modeling approaches, forest inventory data, which can provide *in-situ* estimates of carbon stock and fluxes across heterogeneous regions, has its special advantages (Wang et al. 2008) and is an effective approach for forest carbon estimation in combating climate change (Brown et al. 1999).

Using the methods above, many researchers estimated the carbon stock of forest vegetation and its change at global, national and regional scales (Woodbury et al. 2007). For example, Montagnini and Porras (1998) measured carbon sequestration in three young plantations of 12 indigenous tree species in pure and mixed designs in the humid lowlands of Costa Rica. Hannes et al. (2008) examined the difference in contributions of past disturbances and recent forest management changes to forest biomass carbon stock changes, and also calculated the consequences of different accounting rules for C stock changes in European countries in the period 2013-2017. In China, studies on forest carbon stock have been conducted at three scales: country-wide (Zhao and Zhou 2004), provincial and regional scales (Bai et al. 2008; Zhao et al. 2009; Xu et al. 2010). Based on the national forest inventory data series, Wang et al. (2008) estimated forest biomass change in Liaoning Province from 1984 to 2000 by using dominant tree species biomass models. Forest carbon storage was parameterized specifically by using plant molecular formulae, as a function of individual tree species carbon content. The results showed that forest carbon storage in Liaoning increased from 51.82 Tg C to 70.30 Tg C between 1984 and 2000. By using the same data, Wu et al. (2008) obtained different results: 66.89 Tg C in 1984 and 72.43 Tg C in 2000.

In this paper, we used the National Forest Resource Inventory database for China collected in 1993, 2000, and 2005. We converted forest area and stocking data into forest vegetation carbon stock on the basis of three indexes: forest density, percentile of stem biomass, and forest carbon content. The purpose of this study is to quantify temporal dynamics and spatial variations of Liaoning's forest carbon stock and carbon density in the period of 12 years, discuss the relationships between the distribution of carbon sources and sinks, analyze the trend, and provide advices for pursuing valid forestry managements and building scientific policy. We hope that these results can be used to evaluate the forests' role in reducing atmospheric carbon dioxide.

Materials and methods

Study area

Liaoning Province is located in north temperate continental monsoon climate zone (Fig.1). The annual average temperature of Liaoning Province is 4–10°C and the annual average precipitation is 714.9 mm. The topography of the region is characterized by obliquities from north to south and from east and west to middle. In the east and west area, mountains and hills are the main landscape, which jointly cover 2/3 of the total provincial area. Liaoning Plain and Northeastern Plain are in the middle of the province, accounting for 1/3 of Liaoning Province in area. Liaoning's forest landscape is an intersection of Changbai flora in northeast, North-China flora in the south and Mongolia flora in northwest (Dong 1987). Affected by this topography distribution and the monsoon climate, the hydro-thermal conditions in Liaoning Province vary greatly in different zones. The precipitation is not balanced in the whole region, dry in the west and wet in the east. Eastern area has an annual average precipitation of over 1 100 mm, while southern area of 400 mm, and the precipitation in the middle area is of a moderate amount of 600 mm. Seasonal differences are also shown in the hydrothermal resources of Liaoning Province. The precipitation during the growing season (from May to September) accounts for almost 80% of the whole yearly amount. In this period, the regional average temperature is around 23.5°C and the sunshine time is 1 000–1 350 h. Forests in eastern Liaoning are dominated with cold-temperate coniferous-broadleaved mixed forest; forests in the west and central plains are primarily warm-temperate deciduous broadleaved forest; sparse forests in the northwest contain components of Mongolia flora. Soil in Liaoning province mostly belongs to meadow soil, drab soil, and brown forest soil (Wang et al. 2008).

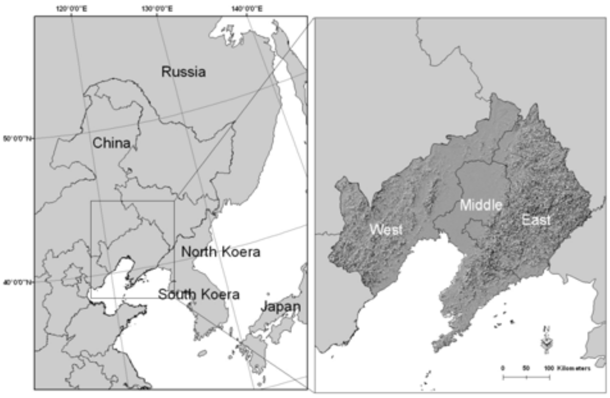

Fig. 1 Location and Eco-zones of Liaoning Province

Study methods

We used the 2nd-class forest inventory data in 1993 and 2005 in Liaoning Province and China's sixth National Forest Inventory data in 2000. The information on forest resources is collected from a permanent plot network. China's sixth National Forest Inventory is managed and implemented by the State Forestry Administration of China. The 2nd-class forest inventory intends to provide data for monitoring forest resources, evaluating forest management activities, and developing forest management planning at a forestry unit. Its statistical unit is sub-compartment. The inventory takes place every ten years with systematic schemes (Tang et al. 2006). According to the Technical Regulations of National Forest Inventory (State Forestry Administration of China 2003), the stages of the inventory are basically including setting plots, surveying, calculating and analyzing. There are 4,617 plots in Liaoning Province. The area of each plot is 0.0667 ha. Systematic sampling is the main method in the National Forest Inventory because data are collected from the established sample plots. In general, the density of ground plots is set according to the required estimate precision of forest land area, growing stock, plantation area, amount of growth and consumption. The ground (sampling plot) survey is composed of two main parts: sampling plot factors and sampling tree factors. Sampling plot factors include sub-factors like land use, land

cover, growing condition, soil, characteristics and functions of forest and ecological status. Sampling tree factors include tree number, species, diameter at breast height, etc. The dynamic of increase volume and felled lumber are calculated and analyzed by mathematical statistics methods.

One-way ANOVA analysis was carried out to measure the influence of different age groups on carbon density. After the equality checking of variances, the two-two comparisons among the means were performed by LSD (Least-Significant Difference) method.

Forest inventory data only include the volume of growing stock and lack information about noncommercial components, including trunks, branches, roots and leaves, which should be included into the conversion from forest timber volume to forest biomass. The carbon content per biomass unit is called carbon storage conversion coefficient (C_c). Forest carbon storage can be calculated by multiplying forest biomass and C_c, ranging from 0.45 (Wang et al. 2001; Zhou et al. 2000) to 0.5 (Fang et al. 2001; Xu et al. 2007). Others used plant molecular formula to estimate C_c for different tree species (e.g. Gu et al. 2008) but the Cc value of 0.5 is often used worldwide (Johnson and Sharpe 1983). Ma et al. (2002) suggested that using C_c value of 0.5 is superior to using 0.45. In this study, we used 0.5 as C_c to convert forest volume to forest carbon storage for Liaoning's forests.

Forest carbon stock was computed as follows:

$$C = V \times D / R \times C_c \tag{1}$$

where, C, V, D, R and C_c refer to forest carbon stock (Mg C), forest volume (m^3), wood density (Mg·m^{-3}), percent of stem biomass (%), and the carbon storage conversion coefficient (Mg C/Mg), respectively. Forest density and percent of stem biomass were referred to the mean forest physical properties and forest biomass of different climate zones in China (Table 1, Wu et al. 2008).

Table 1. Parameters used for estimating forest carbon by vegetation zones in China

Vegetation zone	Wood density (Mg·m^{-3})	Percent of stem biomass (%)
Cold temperate forest	0.47	56.7
Warm temperate forest	0.45	50.0

Data source: Wang (1996)

The carbon density was obtained by calculating the ratio of the forest vegetation carbon stock to the corresponding forest area.

Results and analysis

General changes in forest carbon storage and carbon density

Based on the provincial forest inventory data, the total forest carbon storage in Liaoning Province was 68.91 Tg C in 1993, 72.43 Tg C in 2000, and 97.51 Tg C in 2005, respectively. The forest ecosystems in Liaoning Province showed continuous growth potential in carbon sequestration and acted as a gradual escalation of forest carbon sink (Table 2). Forest carbon density increased from 18.48 Mg·ha^{-1} to 22.33 Mg·ha^{-1} between 1993 and 2005. Although there was a slight decrease in carbon density from 2000 to 2005, the overall trend between 1993 and 2005 was obviously positive. Such an increase in carbon density was due to expanded efforts in developing forest plantations during the 12-year period (FRPILP 2008).

Table 2. Forest carbon storage and carbon density between 1993 and 2005 in Liaoning Province

Year	Area (10^3 ha)	Volume (10^3 m^3)	Carbon storage (Tg C)	Carbon density (Mg·ha^{-1})
1993	3,728.3	166,256.8	68.91	18.48
2000	3,225.7	174,765.7	72.43	22.45
2005	4,365.9	235,276.3	97.51	22.33

Changes in carbon storage and carbon density by age groups

Age class (age class of forest), which designed to simplify the age statement of forest, is the unit of age computation in management. The certain age range, during which each wood of forest has a common feature in growing development and the same mode in management, is called age class. Age class is confirmed by the growing speed and life-span of the tree, and is often used to distinguish the growing speed of trees. Generally it is separated to five groups: young, middle-aged, premature, mature and post-mature. The age class unit of fast-growing tree species is a 5-year time and that of slow-growing ones is a 20-year time.

The carbon density of different age groups of forest lands in Liaoning Province are showed as the figures below. Failing to obtain the data of area and volume of every age group in 2000, we use the data of 1998 instead to calculate the carbon density and carbon storage for comparing between years and showing the dynamics.

Test of homogeneity shows homogeneous variances (p=0.247>0.05). The ANOVA analysis indicates that there are significant differences in carbon density among age groups (p<0.001). Premature forests have the highest carbon density, while young forests have the lowest. Multiple comparisons results reveal that the mean values of both young forests and middle-aged forests have significant differences with other groups (p<0.05), while the value of premature forests has no significant differences from that of mature and post-mature forests (p>0.05). The standard error is 4.392 (Table 3).

Although premature-, mature-, and post-mature-aged forests contribute much to forest carbon density (Fig. 2), their carbon storages account for a small part in the total forest carbon storage (Fig. 3). This is particularly true for the forest in 2005. From 1993 to 2005, the carbon stock increased from 12.51 Tg C to 34.61 Tg C for young-aged forests, from 34.48 Tg C to 40.43 Tg C for middle-aged forests, from 11.57 Tg C to 12.38 Tg C for premature-aged forests. In contract, the carbon stock of mature- and post-mature-aged forests decreased by 0.25 Tg C. In other words, the carbon fixation ability of Liaoning's forests was primarily from young-aged forests that are composed mainly with

forest plantations. Hence, to enhance the carbon sink, it is necessary not only to improve the forest quality, but also to expend the forest area (Wang et al. 2009). This is exactly true in Liaoning Province, where mature forests need to be actively managed to increase their carbon sequestration potentials while young forests need to be increased in area.

Table 3. ANOVA test result of the factors affecting carbon density of Liaoning Province

	Significance of multiple comparisons using LSD method				Standard error
	Young	Middle-aged	Premature	Mature and post-mature	
Young	---	0.000	0.000	0.000	2.01007
Middle-aged	0.000	---	0.002	0.040	1.52189
Premature	0.000	0.002	---	0.089	3.30788
Mature and post-mature	0.000	0.040	0.089	---	1.36189
Total	---	---	---	---	4.39217

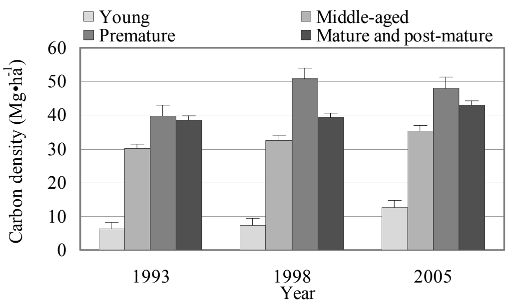

Fig. 2 Forest carbon density in different age groups

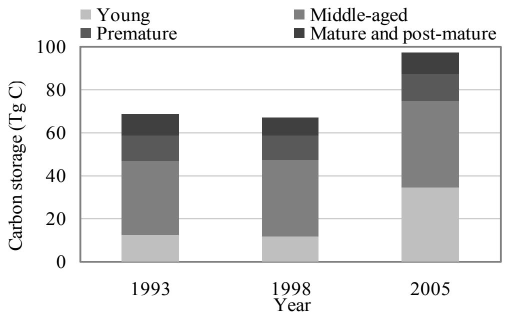

Fig. 3 Carbon storages in different age groups

Table 4. Distribution of forest resources within Liaoning Province in 2005

Region		Category					
		Forest area (10^6 ha)	Woodland area (10^6 ha)	Forest stand area (10^6 ha)	Non-stocked area (10^6 ha)	Standing volume (10^6 m^3)	Forest volume (10^6 m^3)
Total		6.95	5.34	4.37	0.6	244.16	235.28
Eastern region	Quantity	3.75	3.43	2.79	0.11	181.14	179.84
	%	53.99	64.15	63.8	18.84	74.19	76.44
South-central	Quantity	0.7	0.6	0.42	0.05	16.43	14.27
region	%	10.04	11.2	9.55	8.2	6.73	6.06
Northwestern	Quantity	2.5	1.32	1.16	0.44	46.59	41.17
region	%	35.97	24.65	26.65	72.96	19.08	17.5

Data source was from Forestry Atlas of Liaoning, Forestry Researching and Planning Institute of Liaoning Province, Chinese Forestry Press, 2007, 07.

Spatial variations of forest carbon storage and carbon density

On the basis of the topography and the ecological construction of forestry, the territory of Liaoning Province can be divided into three regions: mountainous region in the east, coastal plain region in the south and central part, and semi-arid region in the northwest (Table 4) (FRPILP 2008).

Carbon storage in eastern, south-central and northwestern Liaoning Province was 74.54 Tg C, 5.91 Tg C and 17.06 Tg C, respectively, whereas the corresponding carbon density was 26.76 Mg·ha^{-1} C, 14.17 Mg·ha^{-1} C, and 14.66 Mg·ha^{-1} C, respectively. The largest carbon storage was primarily found in the east, and the highest carbon density also occurred in this region.

Discussions

Characters of forest vegetation carbon stock and carbon density

There was considerable spatial (or regional) and temporal variability in forest carbon storage and carbon density in Liaoning Province. Moreover, this distribution pattern was in accordance with that of climate and land-use conditions. The forest vegetation in Dandong, Fushun, and Benxi Cities in the eastern region with a total area of nearly 2.53 million ha, accounts for 36.34% of total forest area in Liaoning Province. The live stand volume of this area was about 152.91 million m^3, accounting for 62.63% of the provincial total. The same was true for forest carbon stor-

age and carbon density. This was because not only this area was dominated by forest types with high productivity, but also its human population density was lower and forests suffered from fewer disturbances than other regions. As the major carbon stock of Liaoning forests, disturbance in forest ecosystem in this region will certainly influence the function of the whole forests in the province. Consequently, forest management activities, such as the Natural Forest Protection Project, can play an important role in stabilizing the forest carbon sink in this region and the whole province as well. At the same time, the forest vegetation carbon density in this region was higher than provincial mean carbon density. That is to say, forests with high carbon density were mainly located in the regions with relatively high elevations.

Potentialities in the fix-carbon ability of Liaoning's forests

Forest carbon condition has been estimated for many major countries in the Northern Hemisphere by different researchers. The trains of thought in these estimations were basically the same, and the data sources were all from regional or national forest inventories. Our comparison is focused on forest carbon density rather than on carbon storage, due to the considerable difference in the northern forest area in the various literature sources.

The area-weighted mean carbon density of the northern forests estimated from the above approaches falls within a range of 28−114 Mg·ha^{-1} C (Dixon et al. 1994). In our studies, the mean forest carbon density in Liaoning Province was smaller than those reported, and also lower than the national average of 23.69 Mg·ha^{-1} C (Jiao and Hu 2005). Biomass density represents a stock of organic carbon accumulated over time, which is associated with both the accumulation rate of organic carbon and forest age (Fang et al. 2006). For example, most forests of the eastern USA are in recovery stages and have biomass densities that are considerably lower than for mature forests (Brown et al. 1997). Similarly, in the present study, there was still a large proportion of young-aged and low quality of second-growth forests and plantations which limited the total carbon densities. But on the other hand, the younger groups are more vigorously growing (Yin et al. 2010) and have huge potential biomass, thus the forests in Liaoning Province have not reached carbon saturation, and could continue to sequester carbon from the atmosphere if conserved. As a result, the forests in Liaoning also have a great potential to sequestrate carbon as the young-aged forests growing and new management initiatives are applied (Wang et al. 2008). Therefore, it is reasonable to believe that the carbon sequestration of terrestrial ecosystems in Liaoning will continuously increase in the next decades due to the enhanced afforestation, natural forest protection, water and soil conservation, and effective land use and land management (Wang et al. 2008).

Limitations and uncertainties

The estimates of carbon stock by Wang et al. (2008) for 2000 are smaller than our estimates. These differences are mainly because different volume-biomass equations were developed independently in the two studies. We used 0.5 as the mean carbon content to estimate forest carbon stock, and did not consider the differences in C stock between different forest types. While in the research by Wang et al. (2008), the carbon content of different trees was estimated by using the plant molecular formula.

Although absorbing carbon in trees cannot 'solve' the global warming problem on its own, forests can provide an immediate carbon sink while other mitigation technologies are developed (Malhi et al. 2002). However, the location, magnitude and mechanisms of these sinks are still controversial due to the diversity and complexity of forest ecosystems. Major uncertainties remain in the geospatial distribution of terrestrial carbon sources and sinks and the mechanisms that drive the distribution and its change. Differences in data sources or parameters used for simulations (Kim and Sohngen 2009), estimation at different temporal and spatial scales, the spatial heterogeneity (Oijen and Thomson 2010), and complex changes are sources of uncertainty (Lin and Hong 2009). The uncertainties in our research are two folds:

Limitation of forest data

The forest inventories do not provide detailed information about forest biomass except the commercial portion (such as timber volume). So we just calculated the total carbon stock and carbon density of each area instead of each forest type. Inventory-based forest carbon research should also be combined with other independent methods and data, such as remote sensing and eddy covariance data, to make more reliable carbon estimates (Pan et al. 2004). In the future, we should establish a standardized and unified system to estimate carbon density, produce more accurate and useful models, and perform integrated studies at multi-scales and multi-resolutions levels.

Differences between natural forests and man-made forests

The estimated results are also influenced by the differences in physiological and ecological characters of natural forests and man-made forests. As a result, though we have indicated that man-made forests always have negative characters (unitary tree species, poor structure and function, and frequent insect damages) and lower biomass and carbon densities, it is still critical for us to strengthen our research effort in measuring these two forest types separately at a more accurate level.

Although a great deal of effort has been put into researches, there still remains much uncertainty regarding data collection, mechanistic explanations, and model construction in the relevant studies. Due to the complexity of the forest ecosystem and the relatively delay or lack of the related research technology, our knowledge of that is still in the case of immature and questions (Wang and Deng 2002). Spatial variation in inventory uncertainty is a well known phenomenon (Oijen and Thomson 2010), and the most basic cause of uncertainty happens when a mathematical model fails to express accurately a complex environment of reality (Kim and Sohngen 2009). We still need more evaluation and comparison studies to improve estimation and reduce uncertainty.

Conclusions

Well-designed and statistically sound forest inventories over the long period could provide the best data sources for quantifying carbon sinks and their dynamics at large scales. It was clear that forests vegetation in Liaoning Province acted as a carbon sink from 1993 to 2005. There was an increase in annual net carbon sequestration in the period of 12 years. Carbon stock in young-aged and middle-aged forests increased while carbon density of mature and post-mature forests decreased, suggesting that the carbon sequestration capability of Liaoning's forests primarily depends on the plantations. The increase in both carbon stocks and carbon densities in young-aged and middle-aged forests over time explains that the relatively younger forests have great potentials for storing additional carbon. We believe that the continuation of afforestation and reforestation projects will contribute significantly to forest carbon stock and carbon sequestration capability in Liaoning.

The results also indicated that forest ecosystems in Liaoning Province have spatial variations in carbon sequestration due to the influence of combined effects and interactions among several factors such as physical environment, natural interference, human disturbance, and the characteristics of tree species. Among the factors, human disturbance contributes the most to the spatial distribution of the forest carbon density. Therefore, carbon-oriented forest management, maintaining and increasing forest area, reducing natural disturbances in the forest, improving forest productivity, and transferring carbon into wood products can help increase forest carbon stock.

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